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VENTILATION AND SUPPRESSION SYSTEMS IN ROAD TUNNELS: SOME ISSUES REGARDING THEIR APPROPRIATE USE IN A FIRE EMERGENCY

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ABSTRACT

Two important tunnel safety technologies are addressed. The majority of long road tunnels have ventilation systems. In the event of a fire in a tunnel, such systems will influence fire development in a number of different ways. Recent research and observations on these influences are presented. The effects discussed are critical ventilation velocity for smoke control and the influence of ventilation on fire size, fire spread and fire growth. There is no well defined 'best' approach to operate tunnel ventilation in a fire emergency. Another technology of growing importance is sprinklers and water mist systems, which are being installed in an increasing number of tunnels. There are some concerns regarding the integration of ventilation and suppression systems, these are discussed. Of particular concern is the interaction between water mist droplets and ventilation flow which may result in the suppression agent being carried long distances downstream, away from the fire. Ventilation and suppression systems should not be considered to be separate entities, but two parts of an integrated fire safety system. The paper closes with an opinion on how ventilation and suppression systems ought to be controlled to work together for fire safety.

INTRODUCTION

The majority of road tunnels of significant length have some form of ventilation system for various reasons including smoke control in a fire emergency. These fall broadly into two categories, transverse systems and longitudinal systems, although an increasing number of tunnels, for example the refurbished Mont Blanc tunnel [1], have elements of both types installed. Transverse ventilation systems use air ducts, generally either above a false ceiling within the tunnel or below the road deck, to supply and extract air at periodic locations along the length of the tunnel. Sometimes, while the supply duct may extend along the entire length of the tunnel, extraction is only carried out at a small number of locations, such systems are known as semi-transverse systems. Longitudinal systems use jet fans, generally mounted on the ceiling, to move air along the main tunnel void.

In the event of a fire the primary function of any ventilation system is to maintain a smoke free egress path for escaping tunnel users and to allow smoke free access to the fire location for the fire brigade. In fully transverse systems, the strategy is generally to provide maximum extraction in the vicinity of the fire, while air supplies are generally reduced. In semi-transverse systems, the strategy is often to provide maximum extraction on one side of the fire, to allow safe egress on the other side. While the strategy used with longitudinal systems is to blow all the smoke to one side of the fire, once again allowing safe egress on the upwind side.

However, any movement of air in the vicinity of the fire will have an impact on the fire development, smoke production, peak fire size and propensity for fire spread to other vehicles. This paper reviews research onto these aspects of the interaction between ventilation systems and fire behaviour.

In addition to ventilation systems, an increasing number of tunnels are being fitted with fixed fire fighting systems (FFFS). Many of these are conventional deluge sprinkler systems, but many new FFFS are water mist systems (WMS), which produce mush smaller droplets than conventional systems and therefore use significantly less water. The majority of ventilation systems produce fairly high velocities during emergency operation. Yet most FFFS have only been demonstrated to work at low ventilation velocities. This paper discusses some of the unresolved issues of such systems, particularly with regard to integration with existing ventilation systems.

REVIEW: FIRE vs. VENTILATION

Critical Ventilation Velocity

As recently discussed by Ingason [2], the single most well investigated tunnel fire phenomenon is critical ventilation velocity (CVV). This relates to tunnels with longitudinal flow, including all longitudinally ventilated tunnels and many (semi-) transversely ventilated ones. Various experimental, theoretical and computer modelling studies have been carried out, from Thomas in the 1950 and 1960s [3,4] to ongoing work carried out by Wu with various co-investigators [5,6,7]. While approaches vary, it is commonly found that in 'typical' tunnel environments, with fires of significant size, the CVV falls somewhere between 2.5 and 3 ms^{-1}. There is generally found to be a relationship between CVV and fire size, although some studies (e.g. [8]) suggest that there is a 'super critical ventilation velocity' which is sufficient to control the smoke from a fire of any size.

One factor that is masked by this focus on ventilation velocities rather than ventilation systems is the 'throttling' influence of a fire in a tunnel, characterised experimentally by Lee *et al.* in the 1970s [9] and more recently described numerically by Colella *et al.* [10]. Essentially, in order to generate a given airflow velocity in a tunnel, more thrust from the fans is required for a larger fire compared to a smaller fire. Thus, while the CVV for, say, a 30 MW fire may be the same as that for a 60 MW fire, in practice the number of jet fans required to generate the critical flow for the larger fire would be greater.

Many tunnel fire safety strategies circumvent this issue by simply utilising maximum ventilation in any emergency fire situation. However, this may have adverse effects on the fire itself and may not be the best strategy.

Ventilation Velocity vs. Fire Size

It has previously been demonstrated that there is a relationship between the heat release rate (HRR) of a fire and longitudinal ventilation velocity in a tunnel [11,12,13]. This has been observed to vary both with tunnel size and fuel load. While there tends to be a small influence on heat release rate with applied ventilation for pool fires (small pool fires tend to be reduced in HRR with applied velocity, larger pool fires may be increased by up to 50% [11]), there is a much larger enhancing influence of ventilation on vehicle fires, especially heavy goods vehicle (HGV) fires, and particularly in smaller tunnels, see Figure 1 [12]. In Figure 1 (and other publications) the HRR enhancement due to ventilation is described in terms of a factor k, defined as $k = Q_{vent} / Q_{nat}$, where Q_{vent} is the peak HRR of a fire in a tunnel with a given longitudinal ventilation velocity and Q_{nat} is the HRR of a similar fire in a similar tunnel subject to natural ventilation conditions. Thus, for a HGV fire in a two lane tunnel with a longitudinal ventilation rate of 4 ms^{-1}, the peak HRR would be expected to be slightly over twice that of a similar fire in naturally ventilated conditions.

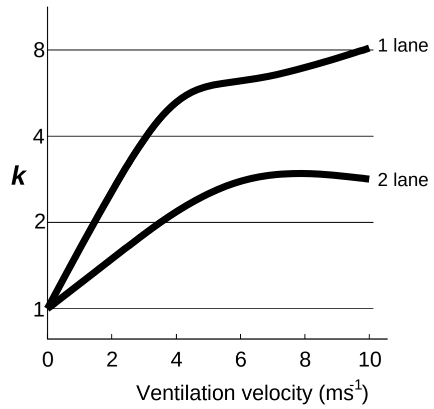


Figure 1 – The enhancing influence of longitudinal ventilation velocity on HGV fires in single and two lane tunnels. The enhancement is described in terms of the factor 'k' – for further details see [11-13]. *(Note the logarithmic scale on the vertical axis; these graphs are representations of the 'expectation' values from a probabilistic study, in practice there will be a distribution of k values for each velocity).*

Smoke production is directly proportional to HRR. As the general trend appears to be that higher airflow rates result in higher peak HRRs, it would seem sensible, in general, to endeavour to keep ventilation velocity low during tunnel fire incidents, in an attempt to keep the fire severity and smoke production as low as possible.

Ventilation Velocity vs. Fire Spread

A study was carried out in 2003-04 investigating (amongst other things) the influence of longitudinal ventilation velocity on fire spread by flame impingement from an initial fire to a HGV 'target' positioned some metres downstream of it [14,15]. In general it was found that, for a fire of given size, the probability of fire spread by flame impingement to the target object was likely to increase with increasing ventilation velocity, see Figure 2. Thus, once again, it would seem sensible to keep ventilation velocity low during tunnel fire incidents, to reduce the risk of fire spread to downstream vehicles.

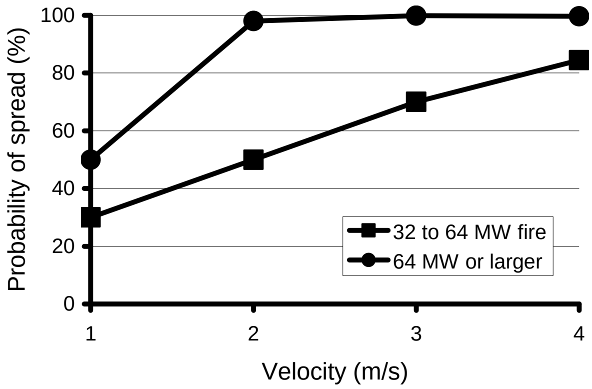


Figure 2 – Variation of probability of fire spread from an initial fire to a 'target' HGV, positioned 5m downstream, with longitudinal ventilation velocity, in a two lane tunnel.

Other studies [16,17] have investigated fire spread by remote ignition. This also varies with ventilation velocity, but it is generally found that the critical HRR for fire spread by remote ignition increases with increasing ventilation velocity. Hence, the likelihood of spread (of a fire of unknown size) decreases with increasing ventilation velocity.

This study considered the combined effects of ventilation on increasing HRR, increasing the critical HRR for fire spread by remote ignition and increasing the likelihood of fire spread by flame impingement to an adjacent HGV 'target'. It was found that fire spread by remote ignition is only likely at very low airflow velocities, while at higher velocities the chance of fire spread by flame impingement dominates. It was observed that for a HGV fire in a typical two lane tunnel, the overall probability of fire spreading to the target HGV (by either spread mechanism) was lower when the ventilation velocity was about 2 ms^{-1} than all other considered ventilation velocities, see Figure 3.

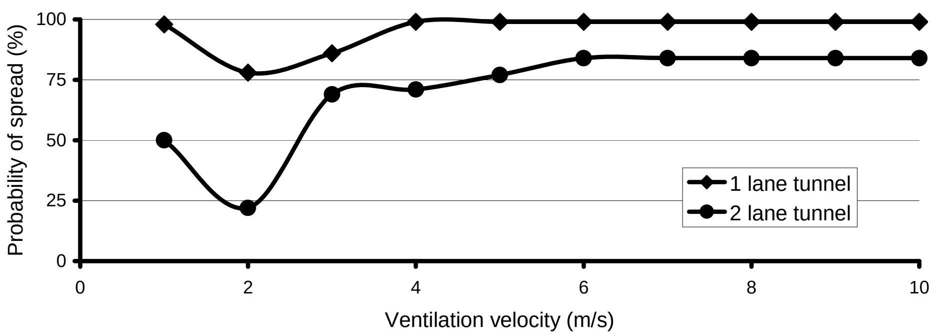
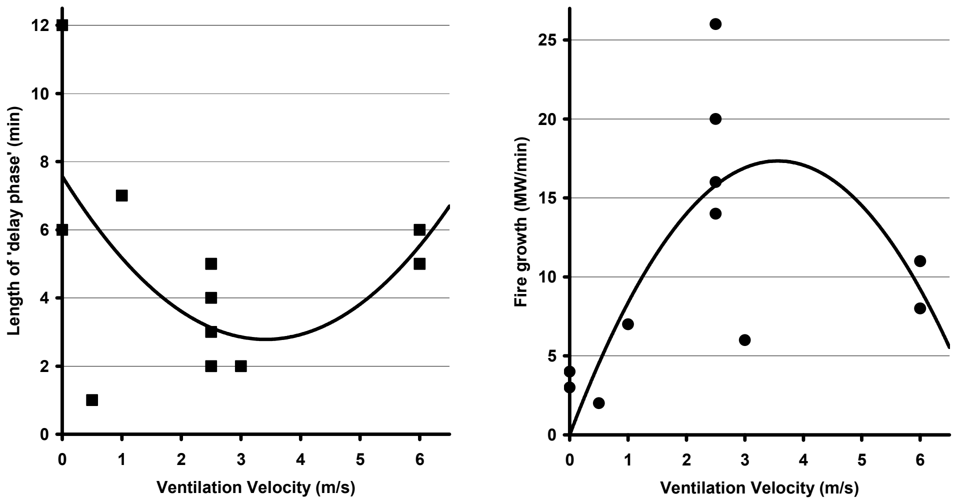


Figure 3 - Variation of probability of fire spread from an initial HGV to another HGV, positioned 5m downstream, with longitudinal ventilation velocity, taking into account the enhancing influence of the ventilation on size of the initial fire, for one and two lane tunnels.

Ventilation Velocity vs. Fire Growth

It was recently observed that there is also a relationship between longitudinal ventilation velocity and the rate of fire growth in the initial stages of a fire [18]. It was observed that the initial fire growth of a 'HGV cargo' type fire in a tunnel may be split into two distinct stages: (i) the 'incipient' or 'delay' phase, during which the fire remains relatively small, often for several minutes, followed by (ii) the growth phase, where the fire grows rapidly, generally in an approximately linear manner with regard to time.

It was observed that longitudinal ventilation velocity has an influence over the duration of the incipient phase; ventilation rates of about 2.5 – 3 ms^{-1} generally result in shorter durations than higher and lower ventilation rates, see Figure 4 (a). It was also observed that the rate of growth in the growth phase is also influenced by longitudinal ventilation flow; ventilation rates of about 2.5 – 3 ms^{-1} appear to result in much faster growth rates than higher or lower ventilation velocities, see Figure 4 (b).



(a) (b)

Figure 4 – The influence of ventilation velocity on fire growth:
(a) observed variation of duration of the 'delay' phase with ventilation velocity
(b) observed variation of fire growth rate with ventilation velocity
Note: the graphs shown are polynomial fits to the available data and should not be understood as anything other than simple trend lines.

Thus, in order to maximise the duration of the incipient phase and to minimise the rate of growth in the growth phase, ventilation rates in the locality of 2.5 to 3 ms^{-1} should be avoided.

These observations are made on the basis of fire tests carried out in the Runehamar tunnel in 2003, the 2nd Benelux tunnel in 2001 and the Hammerfest tunnel in 1992, see reference 18 for further details. It is acknowledged that these observations are based on a very limited sample of fire tests and further research is required to confirm or refute the observed trends.

Transverse Ventilation Systems

Very little research has been carried out with specific regard to the influence of transverse ventilation on fire behaviour in tunnels. Certainly, any semi-transverse system which produces a longitudinal flow past the fire location will result in the same responses as a flow generated by a longitudinal ventilation system. Beyond that, the main concern with transverse systems is whether they are actually capable of extracting the volume of smoke produced by a fire in a tunnel. Many older transverse systems were designed on the basis of a design fire between 20 and 50 MW in size, yet research and experience in the past decade has shown that real vehicle fires may be many times larger than this [19] and so existing transverse ventilation systems may simply not be able to handle real large fires.

Summary

So, on the basis of the reviewed research on fire behaviour in tunnels, the following observations may be made:

Low longitudinal ventilation velocities should not enhance fire growth rates and should not assist fire spread, but may not control smoke.

High longitudinal ventilation velocities should control smoke and may even slow fire growth rates, but may substantially increase the peak fire size and significantly increase the likelihood of fire spread to adjacent vehicles due to flame extension.

Critical longitudinal ventilation velocities should control smoke, but may result in the fastest fire growth rates, the shortest incipient phases and may increase the likelihood of spread to adjacent vehicles.

Transverse ventilation systems may not influence fire growth or spread significantly, but may not control smoke adequately under certain circumstances.

A good compromise

The refurbished system in the Mont Blanc Tunnel [1] utilises aspects of both fully-transverse (with dampers on the extract points) and longitudinal systems. In a fire emergency, the extraction system is configured such that it will provide extraction only at the dampers on either side of the fire location, while the jet fans will drive fresh air towards the fire location from both sides. This should, in principal, result in maximum smoke extraction on either side of the fire yet generate negligible longitudinal flow at the fire location (minimising growth, peak fire size and fire spread). Thus, the smoke logged zone is kept relatively short, and smoke free egress paths on both sides of the fire should be maintained.

Systems such as this one rely on detection systems being able to identify the location of a fire with a high degree of accuracy, and also require careful monitoring and control of the longitudinal flow in the tunnel. The systems in the Mont Blanc tunnel have been demonstrated to work well in test scenarios, but have yet to demonstrate their utility in a real fire incident.

REVIEW: FIRE vs. SUPPRESSION

The 1999 PIARC report on *'Fire and Smoke Control in Tunnels'* [20] expressed the opinion which had been prevalent for the previous couple of decades, that suppression systems "cannot be considered as an equipment useful to save lives" and that, if installed, they "can only be used to protect the tunnel once evacuation is completed." In the past decade the tide of opinion has turned regarding suppression systems for tunnel environments. Suppression systems are now installed or being installed in several tunnels, particularly in Australia and across Europe. PIARC have recently published advice on installing FFFS in road tunnels [21]. However, a number of issues regarding suppression systems remain unresolved.

The current trend in Europe seems to be towards the installation of water mist systems (WMS) rather than conventional deluge systems (such as are installed in urban road tunnels in Australia). While a number of tests results associated to the performance of both systems have been reported in the past [22,23,24,25], there does not appear to be any experimental evidence that WMS are more effective than (or even as effective as) deluge systems for tunnel fire applications, so it is assumed that the primary reason for this recent trend is due to cost.

Water mist vs. ventilation

The droplets produced by WMS are, as the name suggests, considerably smaller than those produced by deluge systems, thus they are far more susceptible to the influence of longitudinal ventilation systems.

A recent modelling study [26] demonstrated that water mist droplets about 90 µm in diameter (reasonably typical for commercially available systems) may be transported about 100 m downstream of the (ceiling mounted) nozzle with longitudinal airflows of about 3 ms^{-1}, before reaching road level. Figure 5 shows the approximate trajectories for 90 µm droplets, subjected to a range of ventilation velocities.

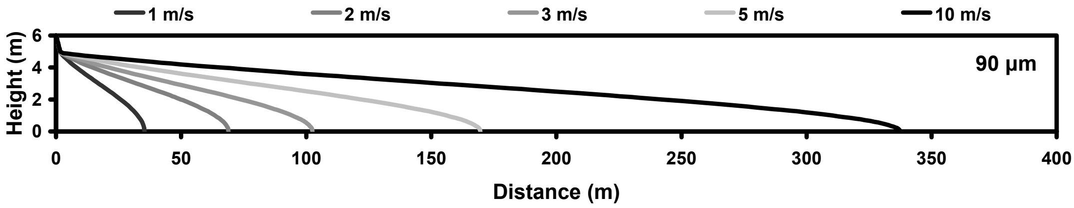


Figure 5 - Travelling distances for 90 µm droplets in a 6m high horizontal tunnel section, subject to average longitudinal airflows of 1, 2, 3, 5 and 10 ms^{-1}.

WMS produce a range of different sizes of droplets. Smaller droplets will be transported even further from the nozzle and higher velocities would carry the tiny droplets even further.

The recent PIARC document *"Road Tunnels: An Assessment of Fixed Fire Fighting Systems"* [21] suggests that one of the requirements of a fixed fire fighting system is that it should "be designed to handle air velocities in the range of 10 ms^{-1}". The implication of this statement is that a suppression system should be designed to operate with the ventilation system running at maximum capacity. The recent study on droplet transport distances has shown that if a 10 ms^{-1} flow was used, most (if not all) droplets produced by a tunnel WMS would be transported more than 100 m downstream of the nozzle before reaching the road deck, see Figure 6. This may have huge implications for the design of WMS for tunnels.

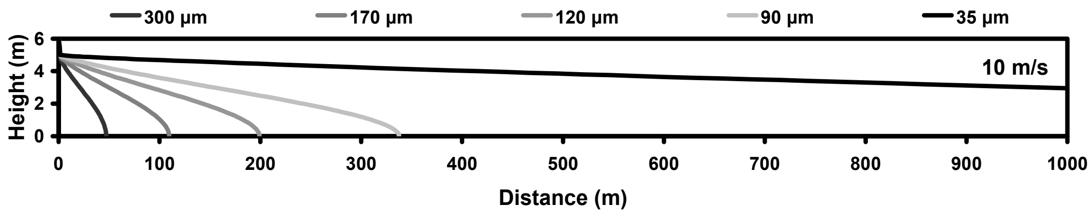


Figure 6 - Travelling distances for 35, 90, 120, 170 and 300 µm droplets in a 6m high horizontal tunnel section, subject to an average longitudinal airflow of 10 ms^{-1}. *(Note: 35 and 170 µm represent the upper and lower bounds of droplet size for most commercially available tunnel WMS; 300 µm is more representative of a conventional deluge system)*

Another issue regarding the interaction of water mist systems and ventilation systems is that WMS have not been experimentally tested at higher ventilation flow rates. WMS have been demonstrated to be able to slow the growth rate and reduce the peak HRR of fires in tunnels, but only with longitudinal flow rates of 3 ms^{-1} or less [24,25]. To date, it has not been demonstrated that WMS are actually effective at suppressing fires when subject to higher ventilation flow rates.

Water mist and critical ventilation velocity

As noted above, the most investigated tunnel fire phenomenon is critical ventilation velocity. The CVV in a tunnel fire scenario is dependent on various factors including the temperature and buoyancy of the fire plume. Water mist, when introduced into this scenario, will interact with the fire, interact with the plume, cool the gases and completely change the flow dynamics. Thus, the CVV in a misty tunnel will be completely different to that in a dry tunnel. It is likely (though not yet demonstrated) that smoke control can be achieved in a misty tunnel at significantly lower flow velocities than in a dry tunnel. Hence, there may be no need to use ventilation velocities above 1 or 2 ms^{-1} to control smoke from a WMS suppressed tunnel fire.

It is claimed that WMS are more effective at dealing with vehicle fires than conventional deluge systems because the small water mist droplets are carried along with the air and entrained into the fire and plume [27]. Entrainment is highly dependent on the ventilation flow. It is therefore quite likely that there is an optimum ventilation rate which will result in more efficient suppression than other ventilation rates. This needs to be demonstrated experimentally, but is unlikely to be high.

If this is shown to be the case, it is important that ventilation and suppression systems should not be considered to be separate systems, but two parts of an integrated fire safety system which must be used together appropriately. The appropriate ventilation rate must be selected on the basis of what, together with the WMS (or sprinkler), provides the most effective suppression of the fire.

WMS are not effective at suppressing very large fires, thus it is important that such systems should be activated as early as possible following detection. For this reason, the detection system must also be part of the integrated fire safety system.

CONCLUDING COMMENTS

For years there has been a focus on two aspects of tunnel fire behaviour, CVV for smoke control and peak HRR as a measure of fire severity. The transport tunnel industry seems to be shifting to a new position where sprinklers and WMS are being used for fire protection. In this new paradigm, peak HRR should not be our concern anymore – if a fire reaches its natural peak HRR, then the suppression system has failed in its task!

Rather, the focus of attention must shift towards the early stages of fire development – the growth phase. When the fire is small, the smoke production rate is small and, hence, the CVV remains small. Based on the observations above, the best way to keep the fire small in its initial stages is to either keep the ventilation velocity low (at about 1 ms^{-1}) or take it up to high velocity (greater than 5 ms^{-1}, but see note below).

It is also desirable to activate the suppression system as early as possible, so it is important to invest in and develop good fire detection systems. If suppression is activated early there is good hope that the fire will not spread, there will not be much smoke production and the fire may be suppressed quickly. Based on the current knowledge of WMS, it is not known if these are effective at high ventilation velocities so, until further research is carried out, a low velocity condition would generally be preferred.

Ventilation, suppression and detection systems should not be considered to be separate entities, but three parts of an integrated fire safety system.

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